PCT

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 7 : G02B 6/16 **A1**	**(11) International Publication Number:** **WO 00/36443** **(43) International Publication Date:** 22 June 2000 (22.06.00)

(21) International Application Number: PCT/JP99/07061

(22) International Filing Date: 16 December 1999 (16.12.99)

(30) Priority Data:
10/359352	17 December 1998 (17.12.98)	JP
09/441,550	17 November 1999 (17.11.99)	US

(71) Applicant: SUMITOMO ELECTRIC INDUSTRIES, LTD. [JP/JP]; 5–33, Kitahama 4–chome, Chuo–ku, Osaka–shi, Osaka 541–0041 (JP).

(72) Inventors: KATO, Takatoshi; Yokohama Works of Sumitomo Electric Industries, Ltd., 1, Taya–cho, Sakae–ku, Yokohama–shi, Kanagawa 244–8588 (JP). OKAMOTO, Kazuhiro; Yokohama Works of Sumitomo Electric Industries, Ltd., 1, Taya–cho, Sakae–ku, Yokohama–shi, Kanagawa 244–8588 (JP). HADA, Mitsuomi; Yokohama Works of Sumitomo Electric Industries, Ltd., 1, Taya–cho, Sakae–ku, Yokohama–shi, Kanagawa 244–8588 (JP). HAGIHARA, Shinjiro; Yokohama Works of Sumitomo Electric Industries, Ltd., 1, Taya–cho, Sakae–ku, Yokohama–shi, Kanagawa 244–8588 (JP). WATANABE, Morio; Yokohama Works of Sumitomo Electric Industries, Ltd., 1, Taya–cho, Sakae–ku, Yokohama–shi, Kanagawa 244–8588 (JP). KOBAYASHI, Kohei; Yokohama Works of Sumitomo Electric Industries, Ltd., 1, Taya–cho, Sakae–ku, Yokohama–shi, Kanagawa 244–8588 (JP).

(74) Agents: HASEGAWA, Yoshiki et al.; Soei Patent And Law Firm, Okura–Honkan, 6–12, Ginza 2–chome, Chuo–ku, Tokyo 104–0061 (JP).

(81) Designated States: AU, CA, CN, ID, IN, JP, KR, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).
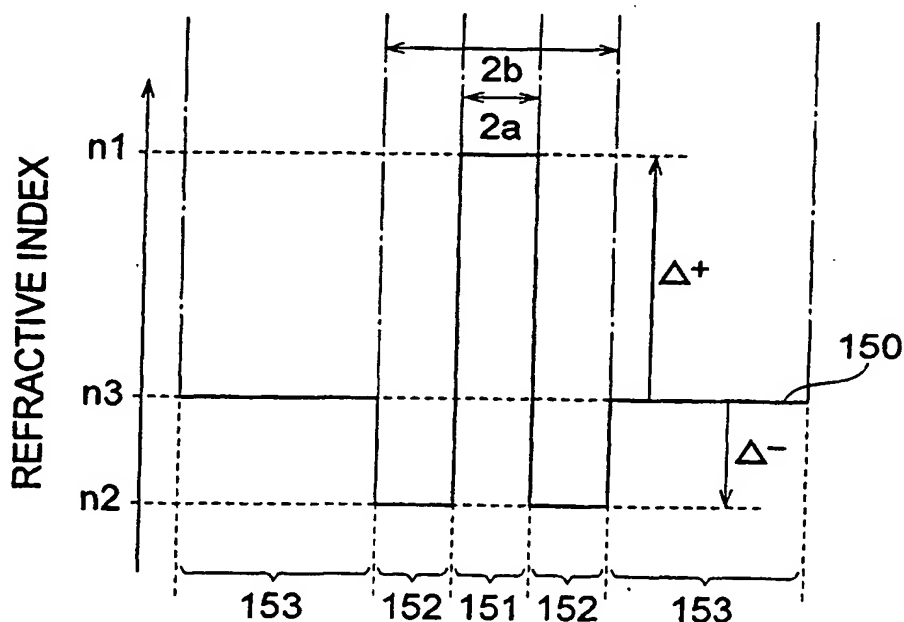
Published
With international search report.

---

(54) Title: OPTICAL FIBER

(57) Abstract

The present invention relates to an optical fiber having a large positive dispersion in a wavelength band of 1.55 μm in order to compensate for a negative dispersion inherent in an NZ–DSF in the wavelength band of 1.55 μm. This optical fiber comprises a depressed cladding structure constituted by a core region; an inner cladding, disposed at the outer periphery of the core region, having a lower refractive index; and an outer cladding having a higher refractive index. In this optical fiber, the relative refractive index difference of the core region with respect to the outer cladding is at least 0.30 % but not greater than 0.50 %, and the relative refractive index difference of the inner cladding with respect to the outer cladding is at least –0.50 % but not greater than –0.02 %. Also, the optical fiber has a dispersion greater than 18ps/nm/km at a wavelength of 1.55 μm, and an effective croos–sectional area A_{eff} of at least 70 μm^2 at the wavelength of 1.55 μm.

BEST AVAILABLE COPY

DESCRIPTION

Optical Fiber

Technical Field

5   The present invention relates to an optical fiber applicable to a module installed in a part of an optical transmission line or on the optical transmission line in an optical transmission system which carries out WDM communications mainly in a 1.55-μm wavelength band.

10

Background Art

WDM (Wavelength Division Multiplexing) communication systems enable large-capacity, high-speed optical communications by transmitting a plurality of signal light components in the 1.55-15 μm wavelength band (1.53 μm to 1.57 μm). Since optical transmission systems carrying out such WDM communications preferably have a low dispersion in the 1.55-μm wavelength band so as to be able to transmit signal light in a wide wavelength band, a dispersion-shifted optical fiber whose zero-dispersion 20   wavelength is shifted to the 1.55-μm wavelength band (DSF: Dispersion Shifted Fiber) has been utilized in their optical transmission lines.

If the dispersion in the 1.55-μm wavelength band is substantially zero, however, then four-wave mixing, which is a 25   kind of nonlinear optical phenomena, may occur, whereby the signal light at the time of reception is likely to deteriorate (see, for

1

example, H. Taga, et al., OFC'98, PD13). Therefore, a
dispersion-shifted optical fiber whose zero-dispersion
wavelength is further shifted to the longer wavelength side so
that the dispersion at a wavelength of 1.55 μm is set to about

5   -2 ps/nm/km (no zero-dispersion wavelength exists in the signal
wavelength band) (NZ-DSF: Non-zero Dispersion Shifted Fiber) has
conventionally been employed in optical transmission lines, so
as to suppress the four-wave mixing. Since the above-mentioned
NZ-DSF has a negative dispersion in the 1.55-μm wavelength band,

10   there are cases where a dispersion-compensating optical fiber
having a positive dispersion in the 1.55-μm wavelength band is
employed in an optical transmission line together with the NZ-DSF
(see, for example, M. Suzuki, et at., OFC'98, PD17).

       As the above-mentioned dispersion-compensating optical

15   fiber, optical fibers defined by G652 and G654 standards of ITU-T,
for example, have been known. The optical fiber of G652 standard
is a regular optical fiber constituted by a core region made of
Ge-doped silica and a cladding region made of pure silica. This
optical fiber of G652 standard has a zero-dispersion wavelength

20   in a 1.3-μm wavelength band and a dispersion of about 17 ps/nm/km
in the 1.55-μm wavelength band. On the other hand, the optical
fiber of G654 standard has a dispersion of 20 ps/nm/km or less
in the 1.55-μm wavelength band. Further, an optical fiber,
constituted by a core region made of pure silica and a cladding

25   region made of F-doped silica, having a dispersion of about 18
ps/nm/km in the 1.55-μm wavelength band is also used as a

2

dispersion-compensating optical fiber.

Since a conventional optical transmission line thus constituted by the NZ-DSF and the dispersion-compensating optical fiber has a positive dispersion slope as a whole, though the dispersion becomes zero in one wavelength in the 1.55-μm wavelength band, it does not become zero in the other wavelength regions. Therefore, in order to compensate for the residual dispersion in the other wavelength regions, the signal light in the other wavelength regions is demultiplexed in a base station or the like, so that the dispersion of each signal light component is compensated for by use of a dispersion-compensating optical fiber of G652 or G654 standard. Here, the dispersion slope is given by the gradient of the curve indicating the dependence of the dispersion upon wavelength.

Disclosure of the Invention

As a result of studies concerning the above-mentioned prior art, the inventors have found the following problems. Namely, since the above-mentioned dispersion-compensating optical fiber of G654 standard has a dispersion of 20 ps/nm/km or less in the 1.55-μm wavelength band, it is needed to have a relatively long length so as to compensate for the negative dispersion inherent in the NZ-DSF in the 1.55-μm wavelength band. Also, in optical fibers having a simple step-like refractive index profile composed of a core region and a cladding region, the upper limit of dispersion is determined according to the upper limit of cutoff

3

wavelength, whereby it is difficult to enhance the dispersion in the 1.55-μm wavelength band.

In order to overcome the problems such as those mentioned above, it is an object of the present invention to provide an

5   optical fiber which has a large positive dispersion in the 1.55-μm wavelength band, and compensates for the negative distribution inherent in the NZ-DSF in the 1.55-μm wavelength band.

The optical fiber according to the present invention comprises a core region extending along a predetermined axis, and

10   a cladding region disposed at the outer periphery of the core region. The cladding region has a depressed cladding structure comprising an inner cladding which is a region disposed at the outer periphery of the core region, and an outer cladding which is a region disposed at the outer periphery of the inner cladding

15   and has a refractive index lower than that of the core region but higher than that of the inner cladding. Also, in this optical fiber, the relative refractive index difference of the core region with respect to the outer cladding is at least 0.30% but not greater than 0.50%, and the relative refractive index difference of the

20   inner cladding with respect to the outer cladding is at least -0.50% but not greater than -0.02%. At a wavelength of 1.55 μm, the optical fiber has a dispersion greater than 18 ps/nm/km and an effective cross-sectional area A_{eff} of at least 70 μm^2.

As indicated in Japanese Patent Application Laid-Open No.

25   8-248251 (EP 0 724171 A2), the effective cross-sectional area A_{eff} is given by the following expression (1):

4

$$A_{\it eff} = 2\pi \left(\int_0^\infty E^2 r dr \right)^2 \Bigg/ \left(\int_0^\infty E^4 r dr \right) \qquad (1)$$

where E is the electric field accompanying the propagated light, and r is the radial distance from the core center.

Since this optical fiber has a large dispersion in the 1.55-
5   μm wavelength band as such, a short length is sufficient when compensating for the negative dispersion inherent in the NZ-DSF in the 1.55-μm wavelength band. As a consequence, it is favorable in that, when the optical fiber is wound at a predetermined diameter so as to form a module, the resulting module can be made
10   smaller. Also, since the effective cross-sectional area at the wavelength of 1.55 μm is large, nonlinear optical phenomena can effectively be restrained from occurring. In addition to the characteristics mentioned above, the optical fiber according to the present invention preferably has a dispersion of 20 ps/nm/km
15   or greater at the wavelength of 1.55 μm. Since this optical fiber has a greater dispersion in the 1.55-μm wavelength band, it can be made shorter when compensating for the negative dispersion inherent in the NZ-DSF in the 1.55-μm wavelength band, whereby it becomes easier to reduce the dimensions of a dispersion-
20   compensating module to which the optical fiber is applied. In particular, for realizing various characteristics at the wavelength of 1.55 μm, each of the optical fibers having the configurations mentioned above preferably satisfies the relationships of:

25        $2.0 \leqq 2b/2a \leqq 6.0$

5

$$8.3 \leqq 2a \leqq 13.0$$

where 2a (unit: μm) is the outside diameter of the core region,
and 2b (unit: μm) is the outside diameter of the inner cladding.

    The optical fiber according to the present invention may

5   have a configuration comprising a core region which extends along
a predetermined axis and has an outside diameter of at least 9.5
μm but not greater than 13.0 μm, and a cladding region having
a refractive index lower than that of the core region. In such
a configuration, the relative refractive index difference of the

10   core region with respect to the cladding region is at least 0.3%
but not greater than 0.5%. Also, the dispersion at the wavelength
of 1.55 μm is at least 20 ps/nm/km, and the effective cross-
sectional area A_{eff} at the wavelength of 1.55 μm is at least 70
μm^2. Since this optical fiber also has a large dispersion in the

15   1.55-μm wavelength band, a short length is sufficient when
compensating for the negative dispersion inherent in the NZ-DSF
in the 1.55-μm wavelength band. Also, since the effective
cross-sectional area at the wavelength of 1.55 μm is large,
nonlinear optical phenomena are effectively restrained from

20   occurring.

    Preferably, each of the optical fibers having various
configurations mentioned above has a transmission loss of 0.215
dB/km or less at the wavelength of 1.55 μm when wound like a coil
at a diameter of 60 mm, and a polarization mode dispersion of 0.25

25   ps $\cdot$ km$^{-1/2}$ or less at the wavelength of 1.55 μm. In this case,
sufficient characteristics can be obtained in the optical fiber

6

according to the present invention even in a configuration in which it is wound like a coil so as to form a module.

As a further preferred optical characteristic, the optical fiber according to the present invention has an effective cross-sectional area A_{eff} of 90 μm^2 or greater. Also, this optical fiber has a cutoff wavelength of 1.4 μm or greater at a fiber length of 2 m. Further, this optical fiber has a transmission loss of 0.180 dB/km or less at the wavelength of 1.55 μm.

The inventors have experimentally confirmed that providing a carbon coating on the surface of the optical fiber according to the present invention is effective in preventing the optical fiber from breaking.

The present invention will be more fully understood from the detailed description given hereinbelow and the accompanying drawings, which are given by way of illustration only and are not to be considered as limiting the present invention.

Further scope of applicability of the present invention will become apparent from the detailed description given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will be apparent to those skilled in the art from this detailed description.

Brief Description of the Drawings

7

Fig. 1A is a view showing a cross-sectional structure of a first embodiment of the optical fiber according to the present invention, whereas Fig. 1B is a chart showing a refractive index profile of the optical fiber shown in Fig. 1A;

Fig. 2 is a graph showing relationships between the core diameter (outside diameter of the core region) and the dispersion at a wavelength of 1550 nm in the optical fiber according to the first embodiment in the case where the ratio (2b/2a) of the outside diameter 2b of the inner cladding to the outside diameter 2a of the core region is fixed at 4.0, whereas the relative refractive index difference Δ^- of the inner cladding with respect to the outer cladding is fixed at −0.03%;

Fig. 3 is a graph showing relationships between the core diameter (outside diameter of the core region) and the dispersion at the wavelength of 1550 nm in the optical fiber according to the first embodiment in the case where the ratio (2b/2a) of the outside diameter 2b of the inner cladding to the outside diameter 2a of the core region is fixed at 4.0, whereas the relative refractive index difference Δ^- of the inner cladding with respect to the outer cladding is fixed at −0.09%;

Fig. 4 is a graph showing relationships between the core diameter (outside diameter of the core region) and the dispersion at the wavelength of 1550 nm in the optical fiber according to the first embodiment in the case where the ratio (2b/2a) of the outside diameter 2b of the inner cladding to the outside diameter 2a of the core region is fixed at 4.0, whereas the relative

8

refractive index difference Δ⁻ of the inner cladding with respect to the outer cladding is fixed at -0.20%;

Fig. 5 is a graph showing relationships between the core diameter (outside diameter of the core region) and the dispersion at the wavelength of 1550 nm in the optical fiber according to the first embodiment in the case where the ratio (2b/2a) of the outside diameter 2b of the inner cladding to the outside diameter 2a of the core region is fixed at 4.0, whereas the relative refractive index difference Δ⁻ of the inner cladding with respect to the outer cladding is fixed at -0.45%;

Fig. 6A is a chart showing the refractive index profile of an applied example of the optical fiber according to the first embodiment, whereas Fig. 6B is a chart showing the refractive index profile of another applied example of the optical fiber according to the first embodiment;

Fig. 7 is a graph showing results of experiments for explaining the breaking prevention effect obtained by carbon coating;

Fig. 8A is a view showing a cross-sectional structure of a second embodiment of the optical fiber according to the present invention, whereas Fig. 8B is a chart showing a refractive index profile of the optical fiber shown in Fig. 8A; and

Fig. 9 is a graph showing the relationship between the core diameter (outside diameter of the core region) 2a and the dispersion at the wavelength of 1550 nm in the optical fiber according to the second embodiment.

9

Best Modes for Carrying Out the Invention

In the following, embodiments of the optical fiber according to the present invention will be explained with reference to Figs.

5   1A, 1B, 2 to 5, 6A, 6B, 7, 8A, 8B, and 9. Among the drawings, constituents identical to each other will be referred to with numerals or letters identical to each other, without repeating their overlapping descriptions.

(First Embodiment)

10   Fig. 1A is a view showing a cross-sectional structure of the optical fiber according to the first embodiment, whereas Fig. 1B is a refractive index profile of the optical fiber shown in Fig. 1A. The optical fiber 100 according to the first embodiment comprises a core region 110 extending along a predetermined axis

15   and having a refractive index n_1 and an outside diameter 2a (μm), and a cladding region disposed at the outer periphery of the core region 110. For realizing a depressed cladding structure, the cladding region further has an inner cladding 120, which is a region disposed at the outer periphery of the core region 110

20   and has a refractive index n_2 ($< n_1$) and an outside diameter 2b, and an outer cladding 130, which is a region disposed at the outer periphery of the inner cladding 120 and has a refractive index n_3 ($< n_1$, $> n_2$). Therefore, the respective refractive indices in the regions 110, 120, and 130 have a relationship of $n_1 > n_3 > n_2$

25   in terms of magnitude. The outer periphery of the optical fiber 100 according to the first embodiment is provided with a carbon

10

coating 140 for effectively preventing the fiber from breaking when it is wound like a coil so as to form a module.

The abscissa of the refractive index profile 150 shown in Fig. 1B corresponds to individual parts along the line L in Fig. 1A on a cross section perpendicular to the center axis of the core region 110. Therefore, in the refractive index profile 150 of Fig. 1B, regions 151, 152, and 153 indicate the respective refractive indices in individual parts on the line L in the core region 110, inner cladding 120, and outer cladding 130.

The optical fiber having such a refractive index profile 150 is a single-mode optical fiber based on silica, which can be realized, for example, by adding Ge and F elements to the core region 110 and the inner cladding 120, respectively. In Figs. 1A and 1B, 2a indicates the outside diameter of the core region 110, whereas 2b indicates the outside diameter of the inner cladding 120. Δ^+ and Δ^- indicate the respective relative refractive index differences of the core region 110 and inner cladding region 120 with respect to the outer cladding 130. Here, the relative refractive index difference Δ^+ of the core region 110 with respect to the outer cladding 130 and the relative refractive index difference Δ^- of the inner cladding 120 with respect to the outer cladding 130 are defined respectively as follows:

$$\Delta^+ = (n_1 - n_3)/n_3$$

$$\Delta^- = (n_2 - n_3)/n_3$$

where n_1 is the refractive index of the core region 110, n_2 is the

11

refractive index of the inner cladding 120, and n_3 is the refractive index of the outer cladding 130. In this specification, the relative refractive index difference Δ is represented by percentage, and the respective refractive indices of individual regions in each defining expression may be arranged in any order. Consequently, the case where Δ is a negative value indicates that the refractive index of its corresponding region is lower than the that of the outer cladding 130.

In the optical fiber 100 according to the first embodiment, the relative refractive index difference Δ^+ of the core region 110 with respect to the outer cladding 130 is at least 0.30% but not greater than 0.50%, whereas the relative refractive index difference Δ^- of the inner cladding 120 with respect to the outer cladding 130 is at least -0.50% but not greater than -0.02%. Also, the dispersion at the wavelength of 1.55 μm is greater than 18 ps/nm/km, and the effective cross-sectional area A_{eff} at the wavelength of 1.55 μm is at least 70 μm^2.

Figs. 2 to 5 are graphs each showing relationships between the outside diameter 2a of the core region 110 according to the first embodiment and its dispersion at the wavelength of 1.55 μm. Here, in the graph of Fig. 2, the ratio (2b/2a) of the outside diameter 2b of the inner cladding 120 to the outside diameter 2a of the core region 110 and the relative refractive index difference Δ^- of the inner cladding 120 with respect to the outer cladding 130 are fixed at 4.0 and -0.03%, respectively. Also, in the graph of Fig. 3, the ratio (2b/2a) of the outside diameter 2b of the

12

inner cladding 120 to the outside diameter 2a of the core region

110 and the relative refractive index difference Δ^- of the inner

cladding 120 with respect to the outer cladding 130 are fixed at

4.0 and -0.09%, respectively. In the graph of Fig. 4, the ratio

5   (2b/2a) of the outside diameter 2b of the inner cladding 120 to

the outside diameter 2a of the core region 110 and the relative

refractive index difference Δ^- of the inner cladding 120 with

respect to the outer cladding 130 are fixed at 4.0 and -0.20%,

respectively. Further, in the graph of Fig. 5, the ratio (2b/2a)

10   of the outside diameter 2b of the inner cladding 120 to the outside

diameter 2a of the core region 110 and the relative refractive

index difference Δ^- of the inner cladding 120 with respect to the

outer cladding 130 are fixed at 4.0 and -0.45%, respectively.

In each of Figs. 2 to 5, G100, G200, and G300 are curves

15   indicating the relationships between the core diameter 2a and the

dispersion value at the wavelength of 1.55 μm in the cases where

the relative refractive index difference Δ^+ of the core region

110 with respect to the outer cladding 130 is 0.30%, 0.40%, and

0.50%, respectively. C1 is a curve showing the relationship

20   between the core diameter 2a and the dispersion value at the

wavelength of 1.55 μm, in which the increase in loss (at the

wavelength of 1.55 μm) in the optical fiber having a total length

of 20 km caused by being wound at a diameter of 60 mm becomes 0.01

dB/km. Further, each of Figs. 2 to 5 shows curves indicating the

25   relationships between the core diameter 2a and the dispersion

value at the wavelength of 1.55 μm in the cases where the cutoff

13

wavelength λc becomes 1.5 μm and 1.6 μm, respectively; and the relationships between the core diameter 2a and the dispersion value at the wavelength of 1.55 μm in the cases where the effective cross-sectional area A_{eff} becomes 70 μm^2, 80 μm^2, and 90 μm^2,

5   respectively. A cutoff wavelength λc up to about 1.60 μm is permissible in the case of an optical fiber having a length of several hundreds of meters, and that up to about 1.70 μm may be permissible in the case of a longer optical fiber. In each of Figs. 2 to 5, an area where the cutoff wavelength λc is 1.6 μ

10   m or shorter, the effective cross-sectional area A_{eff} is at least 70 μm^2, and the increase in loss (at the wavelength of 1.55 μ m) in the optical fiber having a total length of 20 km caused by being wound at a diameter of 60 mm becomes 0.01 dB/km or less is indicated as a preferable range (hatched area in each graph).

15   Judging from Fig. 2, in the optical fiber in which the relative refractive index difference Δ^- of the inner cladding 120 with respect to the outer cladding 130 is -0.03%, when the outside diameter 2a of the core region 110 is about 8.3 μm or greater, then the dispersion at the wavelength of 1.55 μm can become about

20   18 ps/nm/km or greater. When the outside diameter 2a of the core region 110 is about 9.2 μm or greater, then the dispersion at the wavelength of 1.55 μm can become about 20 ps/nm/km or greater. Also, when the outside diameter 2a of the core region 110 is about 12.5 μm, then the dispersion at the wavelength of 1.55 μm can

25   be increased up to about 21.3 ps/nm/km.

          Judging from Fig. 3, in the optical fiber in which the

14

relative refractive index difference Δ^- of the inner cladding 120 with respect to the outer cladding 130 is -0.09%, when the outside diameter 2a of the core region 110 is about 8.3 μm or greater, then the dispersion at the wavelength of 1.55 μm can become about

5   18 ps/nm/km or greater.   When the outside diameter 2a of the core region 110 is about 9.1 μm or greater, then the dispersion at the wavelength of 1.55 μm can become about 20 ps/nm/km or greater. Also, when the outside diameter 2a of the core region 110 is about 12.5 μm, then the dispersion at the wavelength of 1.55 μm can

10   be increased up to about 21.7 ps/nm/km.

Also, judging from Fig. 4, in the optical fiber in which the relative refractive index difference Δ^- of the inner cladding 120 with respect to the outer cladding 130 is -0.20%, when the outside diameter 2a of the core region 110 is about 9.5 μm or

15   greater, then the dispersion at the wavelength of 1.55 μm can become about 20.8 ps/nm/km or greater. Also, when the outside diameter 2a of the core region 110 is about 12.8 μm, then the dispersion at the wavelength of 1.55 μm can be increased up to about 22.3 ps/nm/km.

20   Further, judging from Fig. 5, in the optical fiber in which the relative refractive index difference Δ^- of the inner cladding 120 with respect to the outer cladding 130 is -0.45%, when the outside diameter 2a of the core region 110 is about 10.5 μm or greater, then the dispersion at the wavelength of 1.55 μm can

25   become about 23.2 ps/nm/km or greater. Also, when the outside diameter 2a of the core region 110 is about 13.0 μm, then the

dispersion at the wavelength of 1.55 μm can be increased up to about 23.5 ps/nm/km.

As can be seen from Figs. 2 to 5 in the foregoing, when the relative refractive index difference Δ^- of the inner cladding 120 with respect to the outer cladding 130 is reduced (its absolute value is increased), then the dispersion can be enhanced while keeping the cutoff wavelength λc at the same value.

A plurality of applied examples of the optical fiber according to the first embodiment will now be explained.

To begin with, the optical fiber 100 according to a first applied example has the cross-sectional structure shown in Fig. 1A and the refractive index profile shown in Fig. 1B, whereas the outside diameter 2a of the core region 110, the outside diameter 2b of the inner cladding 120, the relative refractive index difference Δ^+ of the core region 110 with respect to the outer cladding 130, and the relative refractive index difference Δ^- of the inner cladding 120 with respect to the outer cladding 130 are set as follows:

2a (μm)   : 9.0

2b (μm)   : 36.0

Δ^+(%)   : 0.35

Δ^-(%)   :-0.03

Thus designed optical fiber according to the first applied example has, as various characteristics at the wavelength of 1.55 μm, the following optical characteristics:

dispersion (ps/nm/km)   : 18.7

16

effective cross-sectional area A_{eff} (μm^2)   : 80.5

dispersion slope (ps/nm²/km)   : 0.058

transmission loss (dB/km)

when bent at a diameter of 60 mm: : 0.208

5   polarization mode dispersion PMD (ps · km^{1/2}) : 0.14

Here, the cutoff wavelength of the optical fiber according

to the first applied example at a length of 2 m is 1.25 μm. Also,

the above-mentioned transmission loss is the sum of the original

transmission loss of the optical fiber and the increase in loss

10   caused by being bent at the diameter of 60 mm.

The optical fiber according to a second applied example also

has the cross-sectional structure shown in Fig. 1A, and its

refractive index profile has a form similar to that shown in Fig.

1B. Also, this optical fiber of the second applied example is

15   designed with the following features:

2a (μm)   : 10.5

2b (μm)   : 42.0

Δ^+(%)   : 0.35

Δ^-(%)   :-0.03

20   Thus designed optical fiber according to the second applied

example has, as various characteristics at the wavelength of 1.55

μm, the following optical characteristics:

dispersion (ps/nm/km)   : 20.4

effective cross-sectional area A_{eff} (μm^2) : 93.2

25   dispersion slope (ps/nm²/km)   : 0.060

transmission loss (dB/km)

17

when bent at a diameter of 60 mm: : 0.204

polarization mode dispersion PMD (ps · km$^{1/2}$) : 0.12

Here, the cutoff wavelength of the optical fiber according

to the second applied example at a length of 2 m is 1.45 μm. Also,

5   the above-mentioned transmission loss is the sum of the original

transmission loss of the optical fiber and the increase in loss

caused by being bent at the diameter of 60 mm.

The optical fiber according to a third applied example is

designed with the following features:

10   2a (μm)   : 10.5

2b (μm)   : 46.0

Δ^+(%)   : 0.35

Δ^-(%)   : -0.03

Thus designed optical fiber according to the third applied

15   example has, as various characteristics at the wavelength of 1.55

μm, the following optical characteristics:

dispersion (ps/nm/km)   : 21.0

effective cross-sectional area A_{eff} (μm^2) : 103.0

dispersion slope (ps/nm^2/km)   : 0.061

20   transmission loss (dB/km)

when bent at a diameter of 60 mm: : 0.202

polarization mode dispersion PMD (ps · km$^{1/2}$) : 0.12

Here, the cutoff wavelength of the optical fiber according

to the third applied example at a length of 2 m is 1.59 μm. Also,

25   the above-mentioned transmission loss is the sum of the original

transmission loss of the optical fiber and the increase in loss

18

caused by being bent at the diameter of 60 mm.

Further, the optical fiber according to a fourth applied example is designed with the following features:

5

2a (μm)   : 10.0

2b (μm)   : 40.0

Δ^+(%)   : 0.31

Δ^-(%)   :-0.03

Thus designed optical fiber according to the fourth applied example has, as various characteristics at the wavelength of 1.55

10   μm, the following optical characteristics:

dispersion (ps/nm/km)   : 19.6

effective cross-sectional area A_{eff} (μm^2) : 98.0

dispersion slope (ps/nm^2/km)   : 0.060

transmission loss (dB/km)

15   when bent at a diameter of 60 mm: : 0.204

polarization mode dispersion PMD (ps·km$^{1/2}$) : 0.12

Here, the cutoff wavelength of the optical fiber according to the fourth applied example at a length of 2 m is 1.31 μm. Also, the above-mentioned transmission loss is the sum of the original

20   transmission loss of the optical fiber and the increase in loss caused by being bent at the diameter of 60 mm.

The optical fiber according to a fifth applied example has the cross-sectional structure shown in Fig. 1A and a refractive index profile 160 shown in Fig. 6A. As can also be seen from the

25   form of the refractive index profile 160, in the fifth applied example, the core region 110 has such a form that the center part

19

thereof is depressed from its surroundings and the skirt portions

of the core region 110 have an inclined form (form in which the

skirt portions extend toward the inner cladding 120). The

abscissa of this refractive index profile 160 corresponds to

5   individual parts along the line L in Fig. 1A on a cross section

perpendicular to the center axis of the core region 110. Therefore,

in the refractive index profile 160, regions 161, 162, and 163

indicate the respective refractive indices in individual parts

on the line L in the core region 110 (having the outside diameter

10   2a), inner cladding 120 (having the outside diameter 2b), and outer

cladding 130. Here, in the fifth applied example, the relative

refractive index difference Δ^+ of the core region 110 with respect

to the outer cladding 130 is given by the refractive index n_3 of

the outer cladding 130 and the average refractive index n_1 of the

15   core region 110, whereas the relative refractive index difference

Δ^- of the inner cladding 120 with respect to the outer cladding

130 is given by the refractive index n_3 of the outer cladding 130

and the minimum refractive index n_2 of the inner cladding 120.

Such an optical fiber according to the fifth applied example

20   is designed according to the following features:

    2a (μm)   : 10.0

    2b (μm)   : 45.4

    Δ^+(%)   : 0.34

    Δ^-(%)   : -0.03

25   Thus designed optical fiber according to the fifth applied

example has, as various characteristics at the wavelength of 1.55

20

μm, the following optical characteristics:

dispersion (ps/nm/km) : 19.5

effective cross-sectional area A_{eff} (μm^2) : 105.0

dispersion slope (ps/nm^2/km) : 0.062

transmission loss (dB/km)

when bent at a diameter of 60 mm: : 0.198

polarization mode dispersion PMD (ps · km$^{1/2}$) : 0.13

Here, the cutoff wavelength of the optical fiber according to the fifth applied example at a length of 2 m is 1.62 μm. Also, the above-mentioned transmission loss is the sum of the original transmission loss of the optical fiber and the increase in loss caused by being bent at the diameter of 60 mm.

The optical fiber according to a sixth applied example has the cross-sectional structure shown in Fig. 1A and a refractive index profile 170 shown in Fig. 6B. This sixth applied example comprises a core region 110 made of pure silica, and an inner cladding 120 and an outer cladding 130 which are made of F-doped silica. The abscissa of this refractive index profile 170 corresponds to individual parts along the line L in Fig. 1A on a cross section perpendicular to the center axis of the core region 110. Therefore, in the refractive index profile 170, regions 171, 172, and 173 indicate the respective refractive indices in individual parts on the line L in the core region 110 (having the outside diameter 2a), inner cladding 120 (having the outside diameter 2b), and outer cladding 130.

Such an optical fiber according to the sixth applied example

21

is designed according to the following features:

2a (μm)   : 11.6

2b (μm)   : 46.4

Δ^+(%)   : 0.31

5   Δ^-(%)   :-0.05

Thus designed optical fiber according to the sixth applied

example has, as various characteristics at the wavelength of 1.55

μm, the following optical characteristics:

dispersion (ps/nm/km)   : 20.5

10   effective cross-sectional area A_{eff} (μm^2) : 99

dispersion slope (ps/nm^2/km)   : 0.060

transmission loss (dB/km)

when bent at a diameter of 60 mm: : 0.172

polarization mode dispersion PMD (ps $\cdot$ km$^{1/2}$) : 0.08

15   Here, the cutoff wavelength of the optical fiber according

to the fifth applied example at a length of 2 m is 1.50 μm. Also,

the above-mentioned transmission loss is the sum of the original

transmission loss of the optical fiber and the increase in loss

caused by being bent at the diameter of 60 mm.

20   In addition, optical fibers were designed or prototyped

under various conditions, and their various characteristics were

evaluated. As a result, it has been found that sufficiently large

dispersion and effective cross-sectional area A_{eff} are obtained

at the wavelength of 1.55 μm. In particular, it has been found

25   preferable to satisfy the relational expression of 2.0 $\leqq$ 2b/2a

$\leqq$ 6.0, where 2a (unit: μm) is the outside diameter of the core

22

region, and 2b (unit: μm) is the outside diameter of the inner

cladding region. Also, it has been confirmed that the

transmission loss (the sum of the original transmission loss of

the optical fiber and the increase in loss caused by bending) at

5   the wavelength of 1.55 μm when wound like a coil at a diameter

of 60 mm becomes 0.215 dB/km or less in the optical fiber according

to the first embodiment, and that the original transmission loss

of the optical fiber at the wavelength of 1.55 μm becomes 0.180

dB/km or less in further preferable applied examples thereof.

10   Further, it has been found that the polarization mode dispersion

at the wavelength of 1.55 μm is 0.25 ps $\cdot$ km$^{-1/2}$ or less in the optical

fiber according to the first embodiment.

Meanwhile, the inventors have experimentally confirmed that

providing a carbon coating on the surface of the above-mentioned

15   optical fiber is effective in preventing the optical fiber from

breaking.

Fig. 7 is a graph showing results of experiments for

explaining the breaking prevention effect obtained by carbon

coating, in which curve G400 indicates the relationship between

20   the pulling rate (mm/min) and the tensile strength (GPa) when an

optical fiber provided with a carbon coating is broken, and graph

G500 indicates the relationship between the pulling rate (mm/min)

and the tensile strength (GPa) when an optical fiber provided with

no carbon coating is broken. Also, while the fatigue index N of

25   the optical fiber provided with the carbon coating exceeded 150,

that of the optical fiber provided with no carbon coating was about

23

25. Here, the breaking strength (Gpa) at the time when the optical fiber is broken has been known to be proportional to the pulling rate (mm/min), at which the optical fiber is pulled, to the [1/(N+1)]-th power as follows:

$$\text{(breaking strength)} = \alpha \times \text{(pulling rate)}^{1/(N+1)}$$

where N in the expression is particularly referred to as fatigue index.

As can also be seen from Fig. 7, the difference in breaking strength caused by whether there is a carbon coating or not becomes smaller as the pulling rate increases (i.e., apparently, when pulled faster, flaws are less likely to grow and the fiber is less likely to break even if the same force is applied thereto). However, since actually laid optical fibers are caused to break as being pulled at a very low rate, the optical fiber provided with a carbon coating having a high breaking strength at a low pulling rate is further preferable.

As explained in the foregoing, since the optical fiber according to the first embodiment has a large positive dispersion in the wavelength band of 1.55 μm, it needs only a short length for compensating for the negative dispersion inherent in the NZ-DSF in the wavelength band of 1.55 μm, thus making it possible to reduce the dimensions of a dispersion-compensating module to which this optical fiber is applied. Also, since this optical fiber has a large effective cross-sectional area A_{eff} at the wavelength of 1.55 μm, nonlinear optical phenomena are effectively restrained from occurring. Further, since this

24

optical fiber has a low transmission loss at the wavelength of
1.55 μm when wound like a coil at a diameter of 60 mm, and its
polarization mode dispersion at the wavelength of 1.55 μm is small,
it is suitable for forming a module.

5   (Second Embodiment)

The second embodiment of the optical fiber according to the
present invention will now be explained.   Fig. 8A is a view showing
a cross-sectional structure of the optical fiber according to the
second embodiment, whereas Fig. 8B is a refractive index profile
10   of the optical fiber shown in Fig. 8A.   The optical fiber 200
according to the second embodiment comprises a core region 210
which extends along a predetermined axis and has a refractive index
n_1, and a cladding region 220 which is a region disposed at the
outer periphery of the core region 210 and has a refractive index
15   n_2 (< n_1).   As a consequence, the relationship of the respective
refractive indices of the regions 210, 220 in terms of magnitude
is $n_1 > n_2$.   The outer periphery of the optical fiber 200 according
to the first embodiment is provided with a carbon coating 230 in
order to effectively prevent the fiber from breaking when formed
20   into a module by being wound like a coil.

The abscissa of the refractive index profile 250 shown in
Fig. 8B corresponds to individual parts along the line L in Fig.
8A on a cross section perpendicular to the center axis of the core
region 210.   Therefore, in the refractive index profile 250 of
25   Fig. 8B, regions 251 and 252 indicate the respective refractive
indices in individual parts on the line L in the core region 210

25

and cladding region 220.

The optical fiber having such a refractive index profile 250 is a single-mode optical fiber based on silica, which can be realized, for example, by adding Ge element to the core region 210. It can also be realized by making the core region 210 with pure silica and adding F element to the cladding region 220. In Figs. 8A and 8B, 2a indicates the outside diameter of the core region 210, whereas Δ^+ indicates the relative refractive index difference of the core region 210 with respect to the cladding region 220.

Also, in the optical fiber 200 according to the second embodiment, the relative refractive index difference Δ^+ (= $(n_1 - n_2)/n_2$) of the core region 210 with respect to the cladding region 220 is at least 0.3% but not greater than 0.5%, the dispersion at the wavelength of 1.55 μm is at least 20 ps/nm/km, the effective cross-sectional area at the wavelength of 1.55 μm is at least 70 μm^2, and the outside diameter of the core region 210 is at least 9.5 μm but not greater than 12.0 μm.

Fig. 9 is a graph showing relationships between the outside diameter 2a of the core region 210 according to the second embodiment and its dispersion at the wavelength of 1.55 μm. In this graph, G100, G200, and G300 are curves indicating the relationships between the core diameter 2a and the dispersion value at the wavelength of 1.55 μm in the cases where the relative refractive index difference Δ^+ of the core region 210 with respect to the cladding region 220 is 0.30%, 0.40%, and 0.50%, respectively.

26

C1 is a curve showing of the relationship between the core diameter

2a and the dispersion value at the wavelength of 1.55 μm, in which

the increase in loss (at the wavelength of 1.55 μm) in the optical

fiber having a total length of 20 km caused by being wound at a

5   diameter of 60 mm becomes 0.01 dB/km.   Further, Fig. 9 shows curves

indicating the relationships between the core diameter 2a and the

dispersion value at the wavelength of 1.55 μm in the cases where

the cutoff wavelength λc becomes 1.5 μm and 1.6 μm, respectively;

and the relationships between the core diameter 2a and the

10   dispersion value at the wavelength of 1.55 μm in the cases where

the effective cross-sectional area A_{eff} becomes 70 μm^2, 80 μm^2,

and 90 μm^2, respectively.   A cutoff wavelength λc up to about 1.60

μm is permissible in the case of an optical fiber having a length

of several hundreds of meters, and that up to about 1.70 μm may

15   be permissible in the case of a longer optical fiber.   In Fig.

9, an area where the cutoff wavelength λc is 1.6 μm or shorter,

the effective cross-sectional area A_{eff} is at least 70 μm^2, and

the increase in loss (at the wavelength of 1.55 μm) in the optical

fiber having a total length of 20 km caused by being wound at a

20   diameter of 60 mm becomes 0.01 dB/km or less is indicated as a

preferable range (hatched area in the graph).

Judging from Fig. 9, when the outside diameter 2a of the

core region 210 is about 9.5 μm or greater, then the dispersion

at the wavelength of 1.55 μm can become about 20 ps/nm/km or greater.

25   When the outside diameter 2a of the core region 210 is about 12.0

μm, then the dispersion at the wavelength of 1.55 μm can be

27

increased up to about 20.7 ps/nm/km.

In the optical fiber 200 according to the second embodiment, the outside diameter 2a of the core region 210 is 11.0 μm, and the relative refractive index difference Δ^+ of the core region 210 with respect to the cladding region 220 is 0.35%. At this time, the cutoff wavelength λc was 1.54 μm, the dispersion at the wavelength of 1.55 μm was 20.3 ps/nm/km, the effective cross-sectional area A_{eff} was 100.0 μm^2, the dispersion slope was 0.060 ps/nm^2/km, the transmission loss when bent at a diameter of 60 mm was 0.210 dB/km (0.215 dB/km or less), and the polarization mode dispersion was 0.10 ps $\cdot$ km$^{-1/2}$.

Since the optical fiber according to the second embodiment also has a large positive dispersion in the wavelength band of 1.55 μm, it needs only a short length for compensating for the negative dispersion inherent in the NZ-DSF in the wavelength band of 1.55 μm, thereby being suitable for reducing the dimensions of a dispersion-compensating module to which this optical fiber is applied. Also, since this optical fiber has a large effective cross-sectional area A_{eff} at the wavelength of 1.55 μm, nonlinear optical phenomena are effectively restrained from occurring. Further, since this optical fiber has a low transmission loss (at the wavelength of 1.55 μm) when bent at a diameter of 60 mm, and its polarization mode dispersion at the wavelength of 1.55 μm is small, it is suitable for forming a module.

Without being restricted to the above-mentioned embodiments, the present invention can be modified in various manners. For

28

example, though six specific applied examples are represented as the optical fiber according to the first embodiment, and one specific applied example is represented as the optical fiber according to the second embodiment; without being restricted

5   thereto, various designs are possible within the above-mentioned appropriate ranges.

From the invention thus described, it will be obvious that the embodiments of the invention may be varied in many ways. Such variations are not to be regarded as a departure from the spirit

10   and scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended for inclusion within the scope of the following claims.

Industrial Applicability

15   As explained in the foregoing, since the optical fiber according to the present invention has a large dispersion in the wavelength band of 1.55 μm, it needs only a short length for compensating for the negative dispersion inherent in the NZ-DSF in the wavelength band of 1.55 μm. Consequently, it becomes easy

20   to reduce the dimensions of a dispersion-compensating module to which the optical fiber according to the present invention is applied. Also, since the optical fiber according to the present invention has a large effective cross-sectional area A_{eff} at the wavelength of 1.55 μm, nonlinear optical phenomena are

25   effectively restrained from occurring. Further, since this optical fiber has a transmission loss of 0.215 dB/km or less at

29

the wavelength of 1.55 μm when wound like a coil at a diameter

of 60 mm (further preferably, the original transmission loss of

the optical fiber excluding the increase in loss caused by bending

is 0.180 dB/km or less), and its polarization mode dispersion at

5   the wavelength of 1.55 μm is 0.25 ps $\cdot$ km$^{-1/2}$ or less, it is suitable

for forming a module.

30

CLAIMS

1.   An optical fiber comprising:

a core extending along a predetermined axis;

an inner cladding which is a region provided at the outer periphery of said core and has a refractive index lower than that of said core; and

an outer cladding which is a region provided at the outer periphery of said inner cladding and has a refractive index lower than that of said core but higher than that of said inner cladding;

wherein the relative refractive index difference of said core with respect to said outer cladding is at least 0.30% but not greater than 0.50%, the relative refractive index difference of said inner cladding with respect to said outer cladding is at least -0.50% but not greater than -0.02%, the dispersion at a wavelength of 1.55 μm is greater than 18 ps/nm/km and, and the effective cross-sectional area A_{eff} at the wavelength of 1.55 μ m is at least 70 μm^2.

2.   An optical fiber according to claim 1, wherein said optical fiber satisfies the following relationships:

2.0 $\leq$ 2b/2a $\leq$ 6.0

8.3 $\leq$ 2a $\leq$ 13.0

where 2a (unit: μm) is the outside diameter of said core region, and 2b (unit: μm) is the outside diameter of said inner cladding.

3.   An optical fiber according to claim 1, wherein said optical fiber has a dispersion greater than 20 ps/nm/km at the wavelength of 1.55 μm.

31

4.   An optical fiber according to claim 3, wherein said optical fiber satisfies the following relationships:

$$2.0 \leqq 2b/2a \leqq 6.0$$

$$9.1 \leqq 2a \leqq 13.0$$

5   where 2a (unit: μm) is the outside diameter of said core region, and 2b (unit: μm) is the outside diameter of said inner cladding.

5.   An optical fiber according to claim 1, wherein said optical fiber has a transmission loss which becomes 0.215 dB/km or less at the wavelength of 1.55 μm when wound like a coil at

10 a diameter of 60 mm, and a polarization mode dispersion of 0.25 ps $\cdot$ km$^{-1/2}$ or less at the wavelength of 1.55 μm.

6.   An optical fiber according to claim 1, wherein said optical fiber has an effective cross-sectional area of at least 90 μm^2.

15   7.   An optical fiber according to claim 1, wherein said optical fiber has a cutoff wavelength of 1.4 μm or longer at a fiber length of 2 m.

8.   An optical fiber according to claim 1, wherein said optical fiber has a transmission loss of 0.180 dB/km or less at

20 the wavelength of 1.55 μm.

9.   An optical fiber according to claim 1, further comprising a carbon coating provided at the outer periphery of said outer cladding.

10.   An optical fiber comprising:

25   a core region extending along a predetermined axis and having an outside diameter of at least 9.5 μm but not greater than

32

13.0 μm; and

a cladding region which is a region provided at the outer periphery of said core and has a refractive index lower than that of said core region;

wherein said optical fiber has a relative refractive index difference of said core region with respect to said cladding region of at least 0.3% but not greater than 0.5%, a dispersion greater than 20 ps/nm/km at a wavelength of 1.55 μm, and an effective cross-sectional area of 70 μm^2 at the wavelength of 1.55 μm.

11. An optical fiber according to claim 10, wherein said optical fiber has a transmission loss which becomes 0.215 dB/km or less at the wavelength of 1.55 μm when wound like a coil at a diameter of 60 mm, and a polarization mode dispersion of 0.25 ps $\cdot$ km$^{-1/2}$ or less at the wavelength of 1.55 μm.

12. An optical fiber according to claim 10, wherein said optical fiber has an effective cross-sectional area of at least 90 μm^2.

13. An optical fiber according to claim 11, wherein said optical fiber has a cutoff wavelength of 1.4 μm or longer at a fiber length of 2 m.

14. An optical fiber according to claim 11, wherein said optical fiber has a transmission loss of 0.180 dB/km or less at the wavelength of 1.55 μm.

15. An optical fiber according to claim 11, further comprising a carbon coating provided at the outer periphery of said outer cladding.

33

Fig.1A
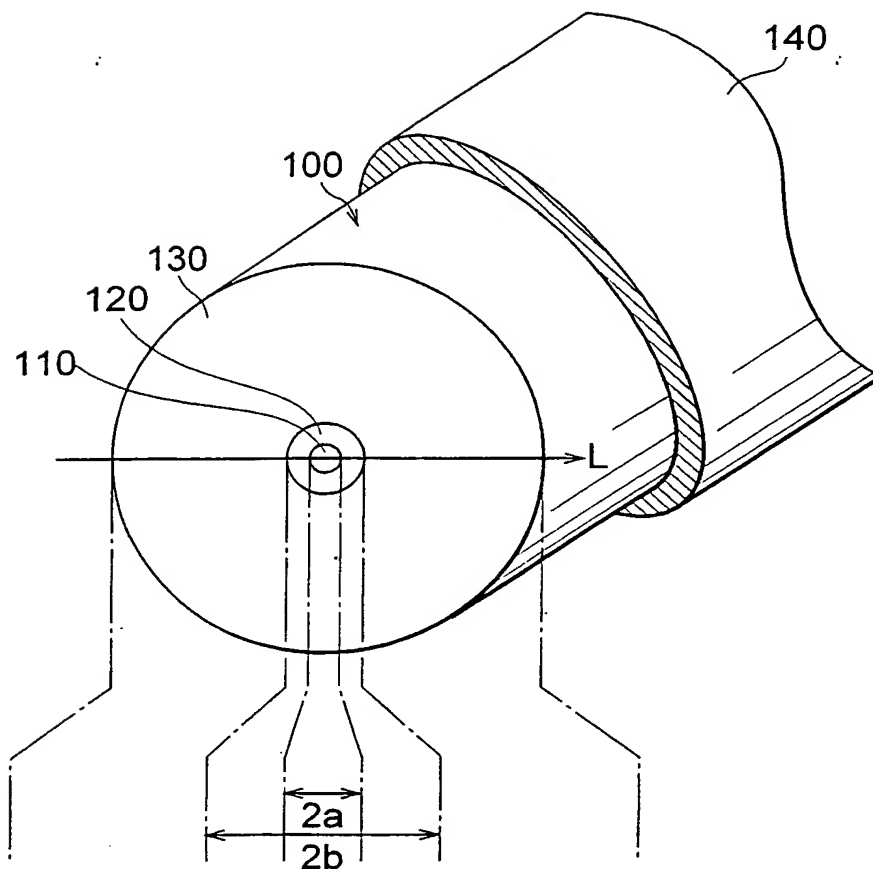
Fig.1B
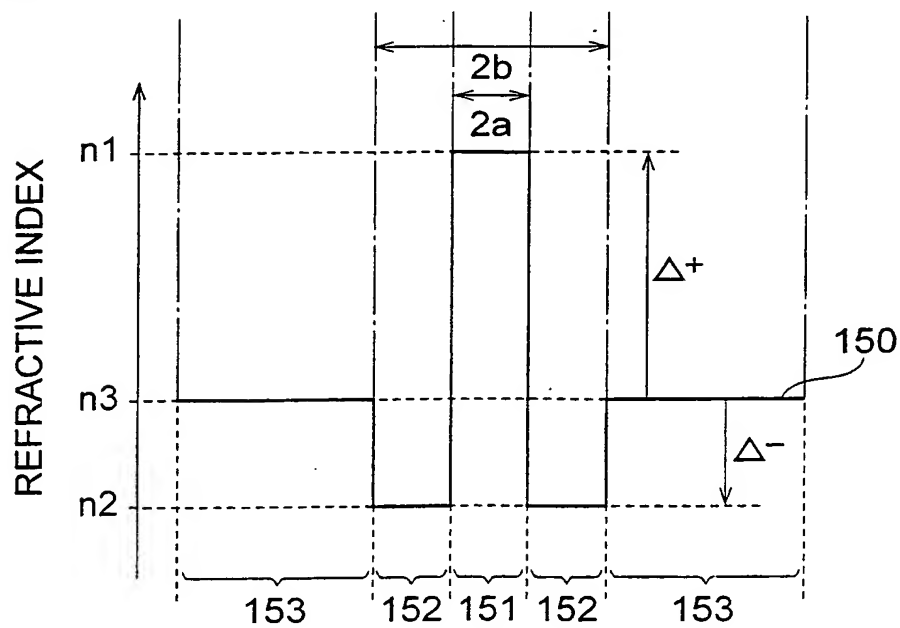
Fig.2
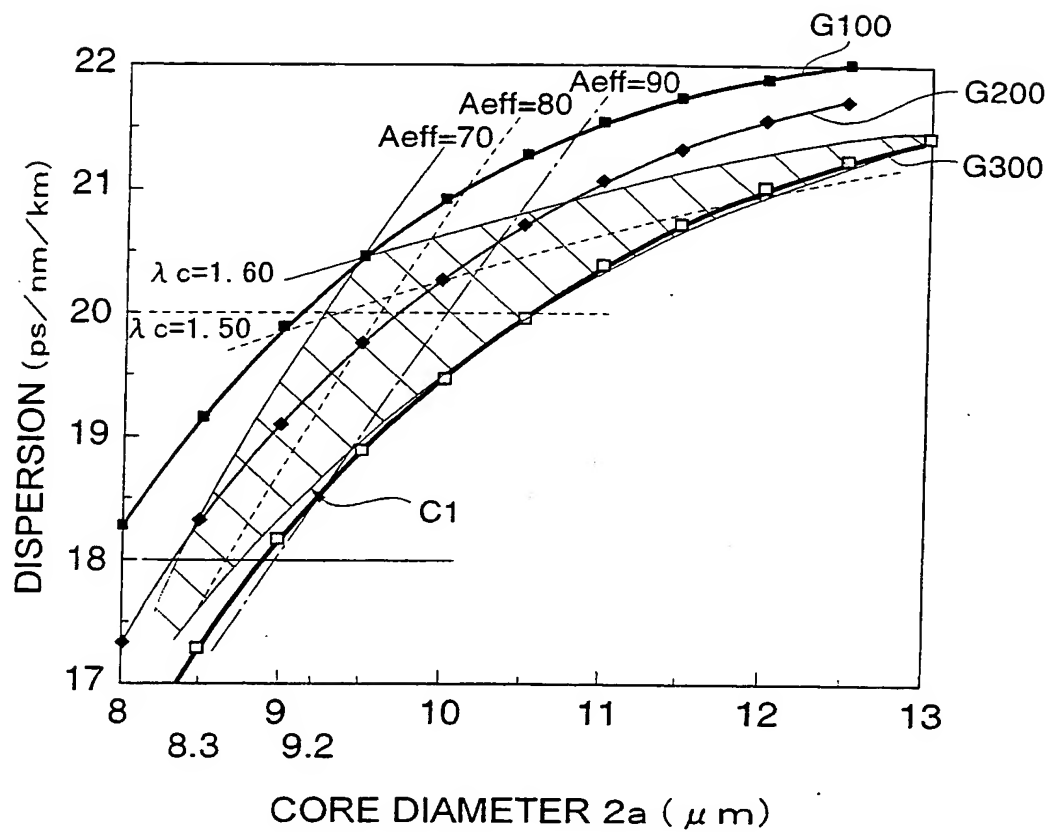
Fig.3
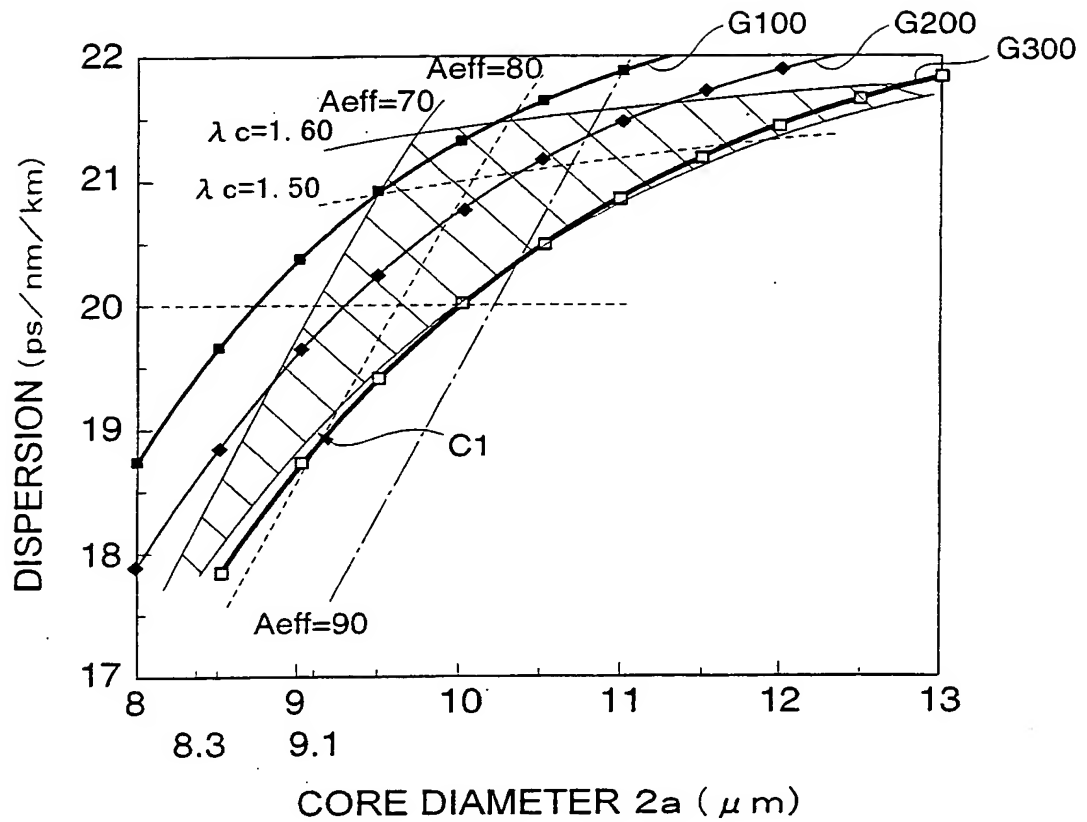
Fig.4
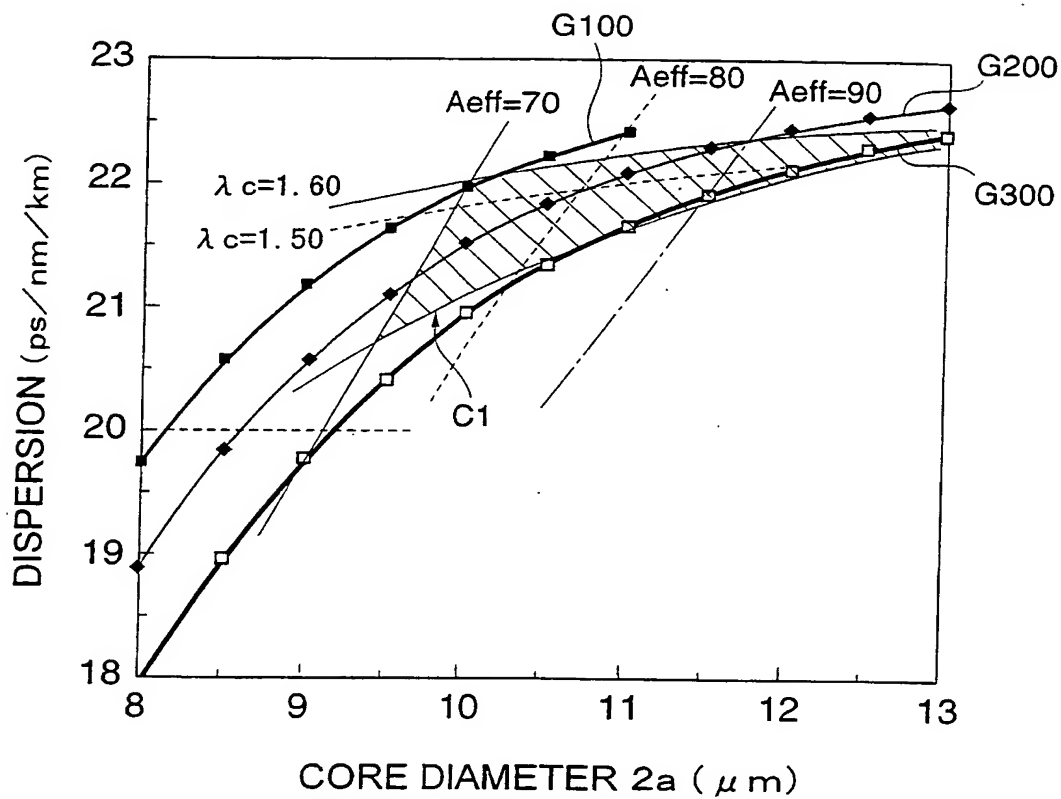
Fig.5

Fig.6A

Fig.6B

Fig.7

6/8
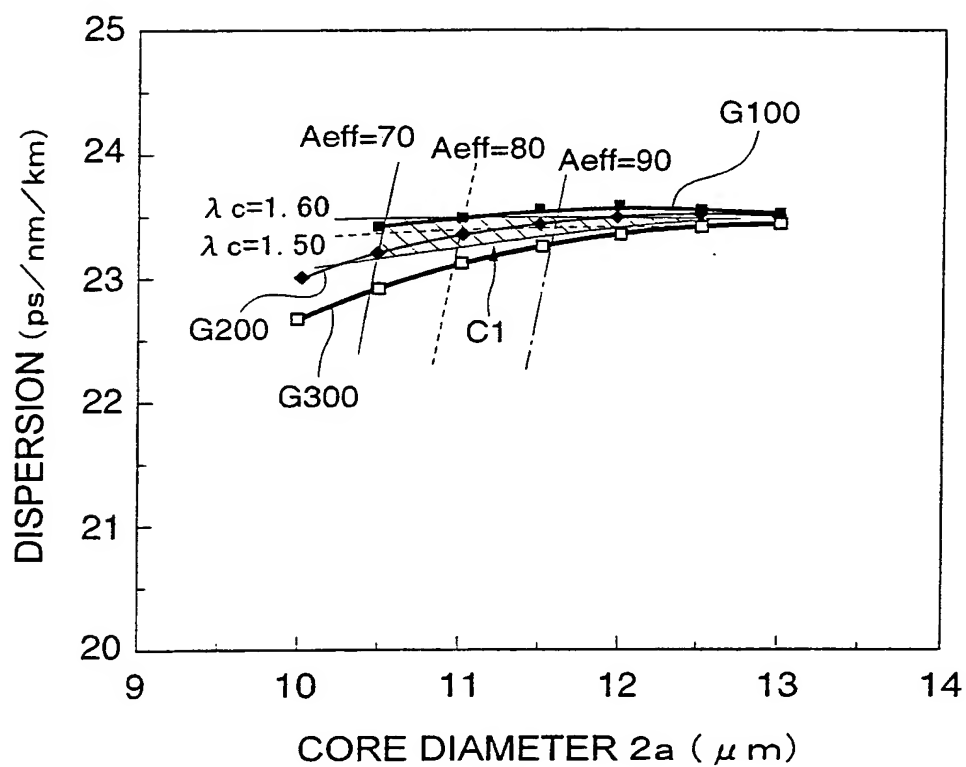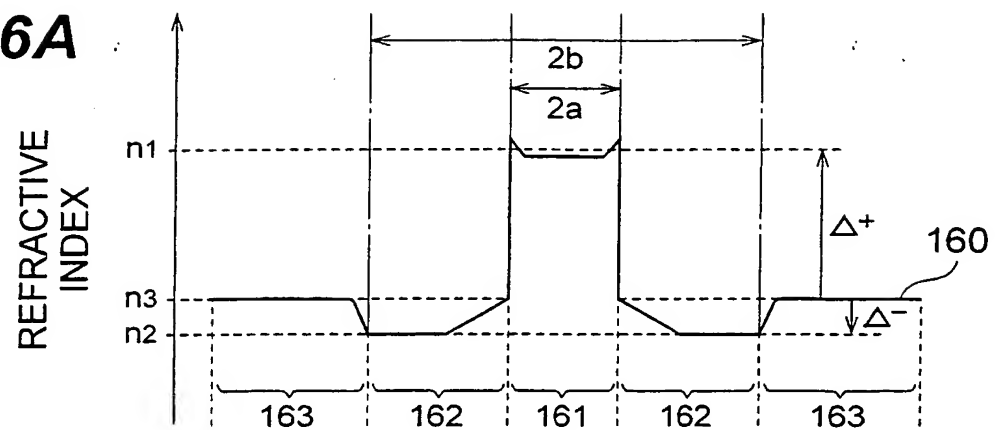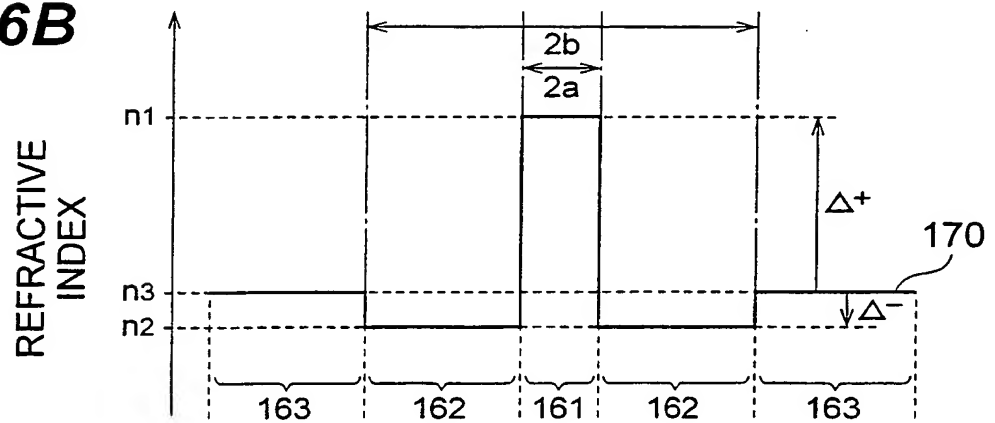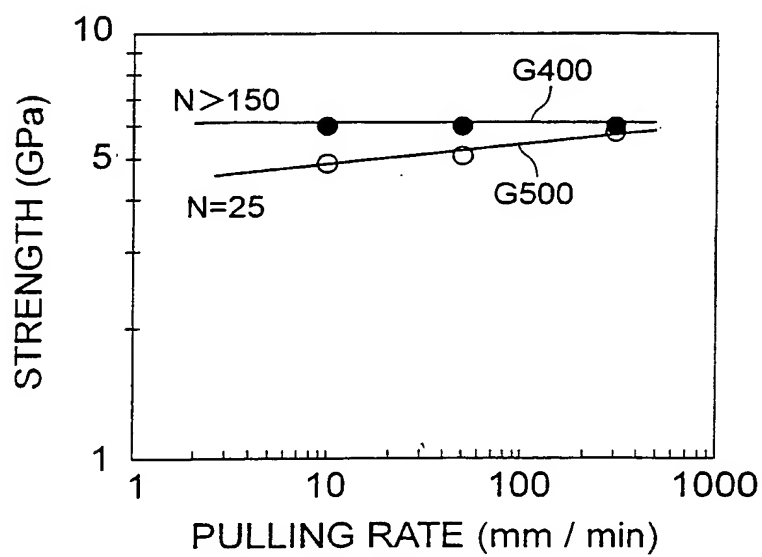
Fig.8A
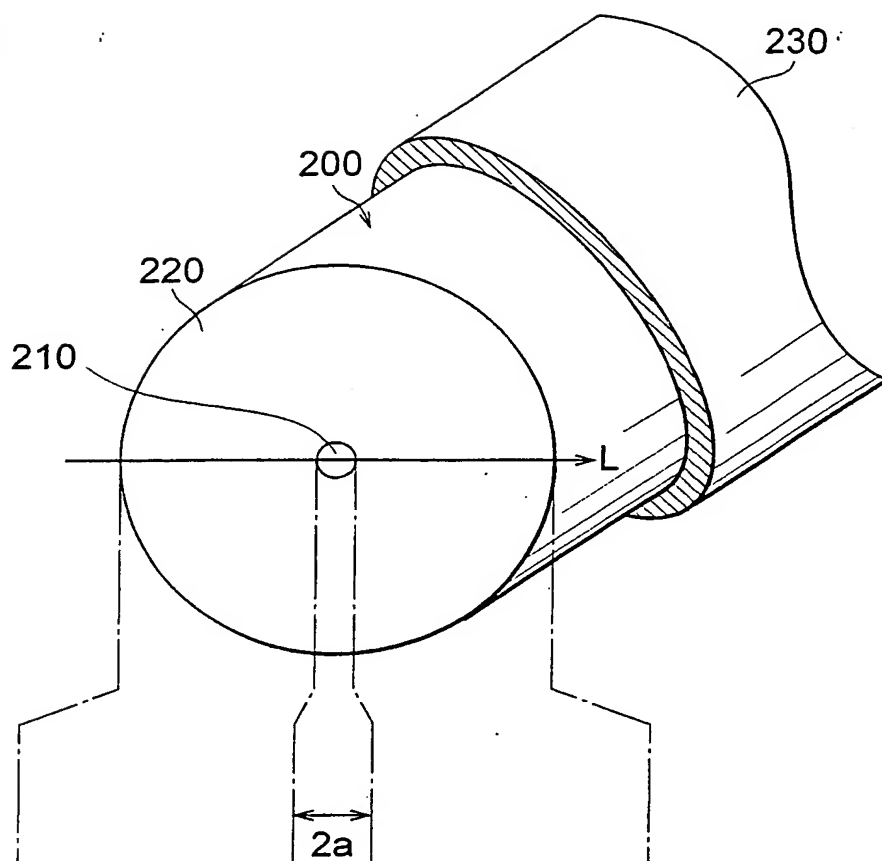
Fig.8B
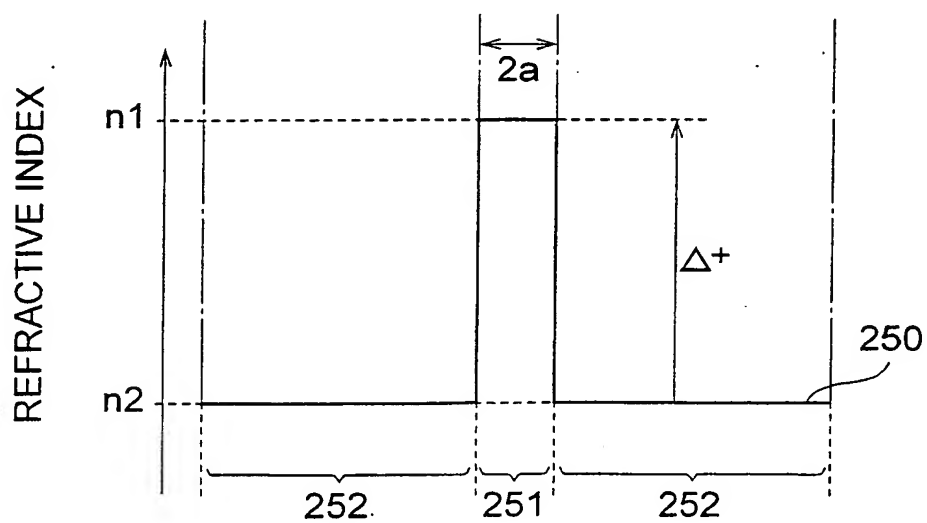
Fig.9
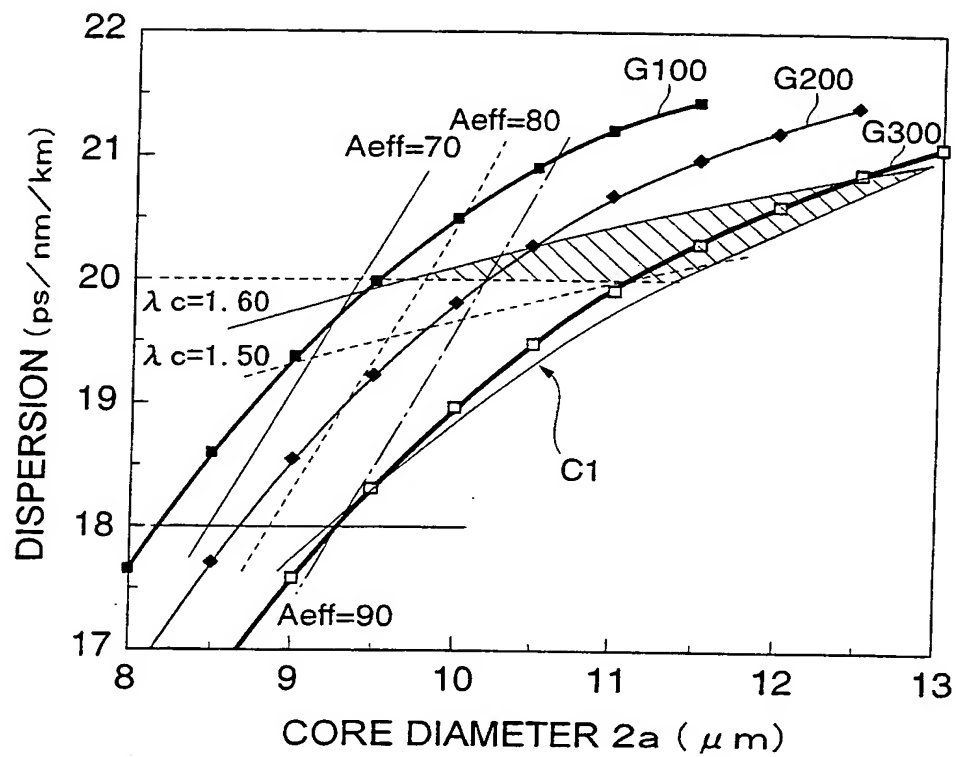
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   G02B6/16

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7   G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 883 002 A (LUCENT TECHNOLOGIES INC) 9 December 1998 (1998-12-09) abstract; figure 3B claim 1 page 2, line 55 -page 3, line 24 page 4, line 38 -page 5, line 53	1
Y		2,4,9
A		3,5-8, 11-14
X	EP 0 779 524 A (CORNING INC) 18 June 1997 (1997-06-18) abstract; figure 4 page 3, line 27 - line 58 page 5; tables 1,2	10
Y		2,4,15
	-/--	

[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

Date of the actual completion of the international search	Date of mailing of the international search report
27 March 2000	04/04/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Jakober, F

1

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5 360 464 A (YAMAUCHI RYOZO ET AL) 1 November 1994 (1994-11-01) abstract; figure 1 column 1, line 35 - line 42	9,15

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
EP 0883002	A	09-12-1998	US	5878182 A	02-03-1999
			AU	711776 B	21-10-1999
			AU	6993898 A	10-12-1998
			BR	9801775 A	14-09-1999
			CA	2237282 A	05-12-1998
			CN	1201913 A	16-12-1998
			JP	11052161 A	26-02-1999
EP 0779524	A	18-06-1997	US	5715346 A	03-02-1998
			AU	7417996 A	19-06-1997
			BR	9605852 A	25-08-1998
			CA	2192425 A	16-06-1997
			CN	1160214 A	24-09-1997
			JP	9274118 A	21-10-1997
US 5360464	A	01-11-1994	JP	4301804 A	26-10-1992
			JP	4051102 A	19-02-1992
			EP	0462893 A	27-12-1991
			US	5223014 A	29-06-1993